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Magnetic Bearing Controller Improvements for High Speed Flywheel System

Timothy P. Dever
QSS Group, Inc., Cleveland, Ohio

Gerald V. Brown
Glenn Research Center, Cleveland, Ohio

Ralph H. Jansen and Peter E. Kascak
University of Toledo, Toledo, Ohio

Andrew J. Provenza
Glenn Research Center, Cleveland, Ohio

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Timothy P. Dever
QSS Group, Inc.
Cleveland, Ohio 44135

Gerald V. Brown
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Ralph H. Jansen and Peter E. Kascak
University of Toledo
Toledo, Ohio 43606

Andrew J. Provenza
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

A magnetic bearing control system for a high-speed flywheel system is described. The flywheel utilizes a five axis active magnetic bearing system, using eddy current sensors for position feedback to the bearing controller. Magnetic bearing controller features designed to improve flywheel operation and testing are described. Operational improvements include feed forward control to compensate for rotor imbalance, moving notch filtering to compensate for synchronous and harmonic rotational noise, and fixed notching to prevent rotor bending mode excitation. Testing improvements include adding safe gain, bearing current hold, bearing current zero, and excitation input features. Performance and testing improvements provided by these features are measured and discussed.

Introduction

High-speed flywheel systems are being developed at NASA Glenn Research Center (GRC) in Cleveland, Ohio. Flywheels show promise as an alternative to batteries and reaction wheels for space systems. Strengths of this technology include high energy density, long life, 90% depth of discharge, and pulse power capability. Flywheels can also be deployed in an array which provides both energy storage and attitude control. A system level flywheel test bed is operational at GRC. The flywheel system utilizes active magnetic bearings (MB) to provide a long-life, low-loss suspension of the rotating mass. The MB control system commands power amplifiers, which produce current in the bearing actuators; forces produced by the actuators suspend the rotor. The system utilizes a feedback loop in which the position of the rotor is measured with eddy current sensors and used as the input to the MB control algorithm. The flywheel modules use a motor/generator coaxial with the rotor to facilitate energy storage and retrieval.

This paper describes the MB controllers used to levitate the flywheel rotors for two different flywheel modules. The paper focuses on algorithms used to improve controller performance. Development and implementation of the improved controller features is described. Test data is presented, quantifying the benefits provided by the improved control features.

Flywheel Module Configuration

This paper describes MB controller development for two different flywheel modules, the High Speed Shaft (HSS) module and the D1 module. These two flywheels are currently under test in a single facility at GRC. The major difference between the two modules is the diameter of the rotors - HSS rotor has a considerably smaller diameter, and thus less energy storage capability, than the D1. The configuration for the D1 module is shown in Figure 1.

The module consists of a flywheel and a motor/generator mounted on the same shaft. The shaft is suspended using a five axis MB system. Shaft location for the five axes is determined using non-contact eddy current sensors. The bearing and sensor axes are defined as X1, Y1 (bottom radial direction), X2 and Y2 (top radial direction), and Z (axial direction). When the MB system is deactivated, the shaft rests on rolling element backup bearings located at the top and bottom of the system. The bottom (radial) MB moves the rotor in the X1-Y1 plane, and the top (combo) MB moves the rotor in the X2-Y2 plane, and axially.

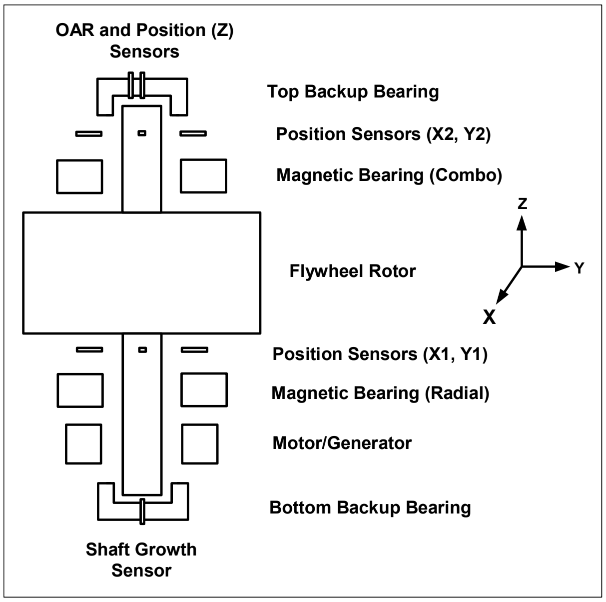

Figure 1. D1 Flywheel Module Schematic

Eleven eddy current position sensors are used in the flywheel modules. Radial sensing is achieved using two sets of four sensors (top and bottom), and axial sensing is done using a single sensor targeting the top of the shaft. A second sensor located at the top of the module targets a step on the shaft; this once-around sensor (OAR) provides the controller with shaft speed and angular position. Potential growth of the shaft due to heating during flywheel operation is measured by the growth sensor at the bottom of the shaft.

Flywheel Controller Configuration

A simplified schematic of one axis of the MB control loop is shown schematically in Figure 2. The bearing control code in the MB controller generates command signals to allow shaft levitation. These command signals are converted to drive currents by the pulse width modulated (PWM) amplifiers. These currents are fed to the MB actuators; forces produced by the actuators suspend the rotor. The position of the rotor is measured using non-contact eddy current sensors; these sensor signals are processed by the signal conditioning system and fed back to the bearing controller as input to the MB control algorithm.

The MB controller is a closed loop control system; however, an operator is present whenever the system is in use. Key elements of the MB operator console include the shaft position display, the bearing current display, the position and current spectral display, and the operator human-machine interface (HMI).

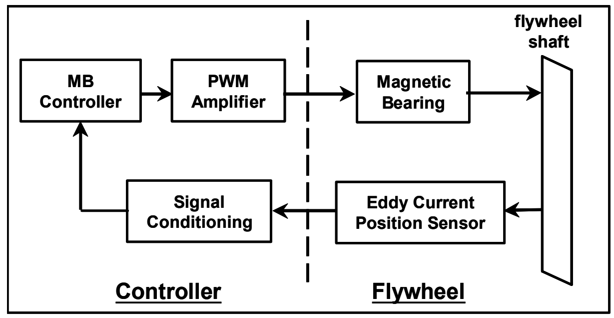

Figure 2. Simplified MB Control System

The shaft position display is shown schematically in Figure 3. The real time radial shaft positions, or "orbits", which are generated from the X and Y position sensor information, are displayed in X-Y mode on oscilloscopes. A circle describing the allowable range of travel of the shaft (defined by the clearance of the backup bearings) is stored in scope memory and is also displayed. The real time shaft position orbit provides information on bearing controller performance, and lets the operator know the radial clearance between the shaft and the backup bearing. Separate scopes are used to display top and bottom radial orbits.

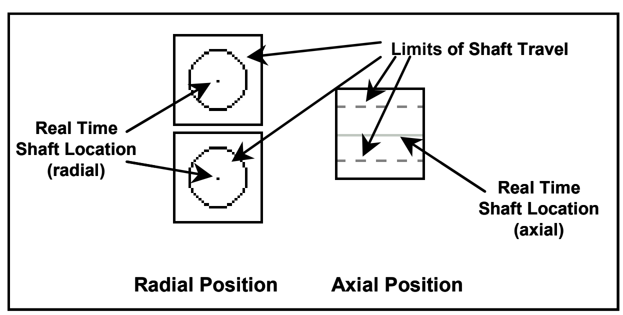

Figure 3. MB Operator Console – Shaft Position

Axial clearance is displayed by a third oscilloscope run in standard X-T mode. Two cursors mark the top and bottom of the travel allowed by the backup bearings, while the present location of the shaft, determined by the Z position sensor output, is displayed in real time as a trace on the scope.

Bearing currents are displayed in the same format as the position displays. Current sensors monitoring each bearing axis are scaled and plotted on oscilloscopes in an X-Y plot for radial MB currents and an X-T plot for the axial MB current.

Spectral plots display the same information as the position and current displays; one plot displays all five axis positions versus frequency, and the other plot displays MB currents for all five axes versus frequency, in real time.

All of the MB controller gains are displayed for the operator, and are adjustable during operation, through the operator HMI.

The flywheel MB controllers are written using a commercially available high level simulation/control tool, which generates C code, and executes on a PC based control card. Details of the core of the control system, including implementation, tuning, and operation are described in [1].

Flywheel Controller Improvements

This section describes improvements to the magnetic bearing controller. They are intended to improve controller performance during operation and testing. Performance improvements include feed forward correction to compensate for rotor imbalance, moving notch filtering to compensate for synchronous and harmonic noise, and fixed notch filtering to prevent rotor bending mode excitation. Improvement features for testing include safe gaining, bearing zero and bearing hold features, and excitation inputting.

Rotor Imbalance and Feed Forward Correction

During assembly, flywheel rotors are balanced on specialized equipment to minimize imbalance in the final assembled rotor. However, some finite imbalance is unavoidable. The imbalance present at either of the radial bearings can be modeled as a mass (m) located at a radial distance (d) from the center of rotation (C) of the rotor. This imbalance is located at an offset angle (θ_o) from the rotor angle reference point, as shown in Figure 4. The lumped imbalance is typically different at the upper and lower bearings; for simplicity, we discuss the imbalance behavior as if the motions at the two bearing locations were independent.

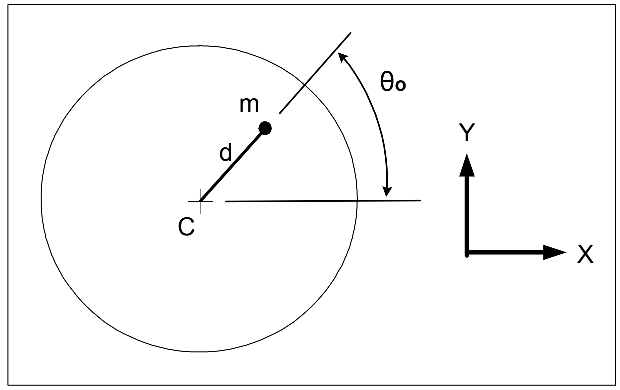

Figure 4. Rotor Imbalance at Radial Bearing

As the flywheel rotates around its geometrical axis at angular velocity ω, the imbalance m generates rotational forces [2] which can be described in terms of the bearing control axis directions as

$$Fx_{imbalance} = md\omega^2\cos(\omega t + \theta_o) \qquad (1a)$$

$$Fy_{imbalance} = md\omega^2\sin(\omega t + \theta_o) \qquad (1b)$$

When an unbalanced rotor is levitated and spinning, control effort is exerted to try to maintain the average position of the shaft at the radial position set point. However, per Equation 1, the position (and current) orbits will grow with speed. Eventually, considerable effort may be exerted to maintain this growing orbit, and, depending on the amount of imbalance, the orbit may eventually grow until levitation cannot be maintained.

Compensation for rotor imbalance can be achieved using a technique called feed forward correction. Feed forward correction works by adding a rotating correction to the position inputs, and can be used to minimize the position orbit sizes, minimize the current orbit sizes, or reduce both the position and the current orbit sizes.

The OAR signal is used to generate the rotor angular position, which is required for calculation of the feed forward control signal. The OAR is generated using a sensor mounted at the top of the unit, next to the axial sensor, targeting a step which has been machined into the top of the shaft (see Figure 1). This sensor generates a signal which is at the frequency of rotor rotation. Since the signal resets, with each revolution, at the same location on the rotor, the signal also provides an angular position reference.

The raw OAR signal is processed in hardware and converted to a voltage signal which is proportional to shaft angular position; this signal is then fed into the MB controller. A schematic of the OAR and position preprocessor is shown in Figure 5. The raw OAR signal is first cleaned up using a Schmitt trigger; the clean signal is then fed to a frequency-to-voltage converter, the output of which is fed to an integrator. With each revolution, the integrator is reset. The integrator output is a saw tooth wave which is proportional to rotor angle. The Schmitt output is also fed directly into the controller's DSP input, which calculates the spin frequency for use in the controller.

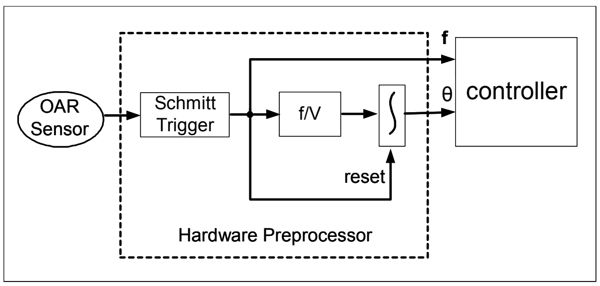

Figure 5. OAR Hardware Preprocessor

Generation of the feed forward correction is accomplished in software, using the algorithm shown in Figure 6. The angular position, θ, is input to the controller through the A/D converter. Feed forward corrections in the form of sine and cosine functions are generated using θ. Coefficients A1, A2, θ_{o1} and θ_{o2} determine the feed forward amplitudes and angular offsets for each bearing. Note that the correction is of the same form as the imbalance force, as described in Equation 1.

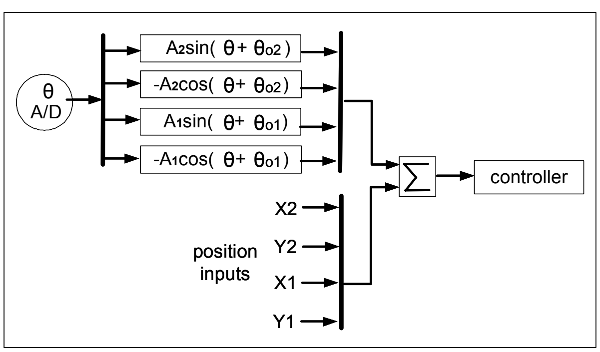

Figure 6. Feed Forward Implementation

Benefits from using feed forward imbalance compensation are shown in Figures 7 and 8. These figures show the D1 flywheel unit's lower bearing position and current orbits, before and after feed forward compensation is added, while the rotor is spinning at 10,000 RPM. The upper portion of Figure 7 shows the uncompensated position orbit, which is about 0.9 mils in diameter. A position orbit of this size is not necessarily a problem. However, as seen in the top portion of Figure 8, the current required to maintain this position orbit is becoming large (about 2 Ap-p), and if no compensation is added, both the current and position orbits will continue to grow with increasing speed. Since 10KRPM is only 1/6 of the rated flywheel speed, unless corrected, this imbalance force will become a control issue before rated speed can be reached.

After feed forward compensation is added (Figure 7, lower), the position orbit radius is cut in half. The bearing current required to maintain this orbit is also reduced considerably (Figure 8, lower).

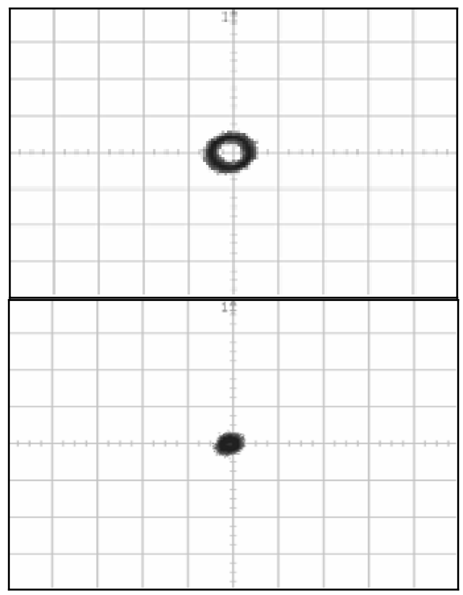

Figure 7. D1 Radial Bearing Position Orbit
Before and After FF Compensation (10,000 RPM)

Using the feed forward technique to decrease position and/or current orbit size growth due to imbalance provides improved controllability and decreased control effort.

Using Feed Forward Compensation

Optimal feed forward coefficients A1, A2, θ_{o1} and θ_{o2} (feed forward amplitude and offset angle values for each of the radial bearings) are determined experimentally. Each time the rotor reaches a new speed, e.g. at 1000 RPM increments, the operator manually tunes the feed forward offset angle and amplitude for each bearing, to minimize orbit size. Position and current orbits can be optimized together, or either orbit can be minimized, depending on the need.

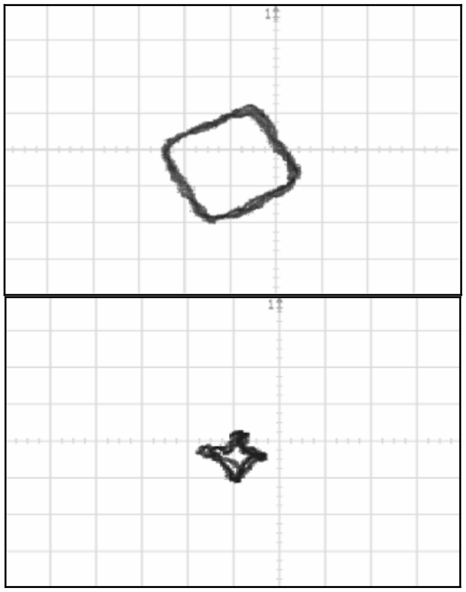

Figure 8. D1 Radial Bearing Current Orbit Before and After FF Compensation (10,000 RPM)

Since the imbalance is repeatable over multiple runs, once determined, these coefficients can be placed into lookup tables and gain scheduled to provide automatic feed forward compensation.

Rotational Noise Correction

As the flywheel rotates, the radial position sensors pick up noise at the rotation frequency (synchronous noise), and at its harmonics (harmonic noise). This noise is caused by imperfections in the sensor target. The controller will interpret this noise signature as actual shaft motion, and will try to compensate for it, thus moving the shaft and generating motion where there was none. This is obviously undesirable; in this situation, unnecessary control effort is exerted, control becomes more difficult, and the shaft is forced from the radial position set points.

Moving Notch Filtering

In order to prevent the controller from responding to this noise, moving notch filters are added between the position sensors and the MB controller inputs - these filters work by simply preventing the synchronous and harmonic noise from entering the controller. The controller uses notches at the rotational frequency and at its second and third harmonics; these filters are implemented in software. One stage for this implementation is shown schematically in Figure 9.

Each notch stage has two input types: the position sensor signals and the rotor speed. The rotor speed is used to center the moving notches (F_{notch}), and to make decisions about filter turn-on. Once switch-on speed (F_{on}) is reached, a switch called a fader transitions the output signals from unfiltered to moving notch filtered over the course of one second. The fader is used to prevent an abrupt change in the position sensor signal input to the controller, since the moving notches are added while the rotor is spinning.

Output of this stage is daisy-chained through two more stages; the F_{notch} values for these additional stages are set to the second and third harmonic frequencies.

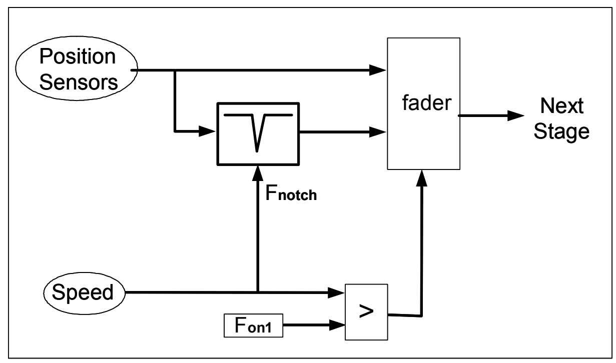

Figure 9. Synchronous and Harmonic Noise Notch Filter (One Stage)

Benefits of this technique can be seen in Figures 10 through 12. Figure 10 is the average radial position spectrum for the HSS while levitated and spinning at 10,000 RPM. This corresponds to 167 Hz, and the figure clearly shows that synchronous and harmonic noise is present.

Figure 11 (upper) shows the radial bearing current spectrum at this speed without moving notches. This figure plots the average of the currents commanded in all four radial bearings, and clearly shows that the controller is in fact commanding current at 167Hz and its multiples in response to the synchronous and harmonic position sensor noise. This means that the rotor is being moved around unnecessarily, adding to the control current delivered and making the MB control more difficult. Figure 12 (upper) shows the lower bearing current orbit under these same conditions; synchronous and harmonic content is visible here, as well. (Note that the current orbit has DC offsets in both the X and Y directions; this is done intentionally, to allow the position orbit to be centered within its allowable travel).

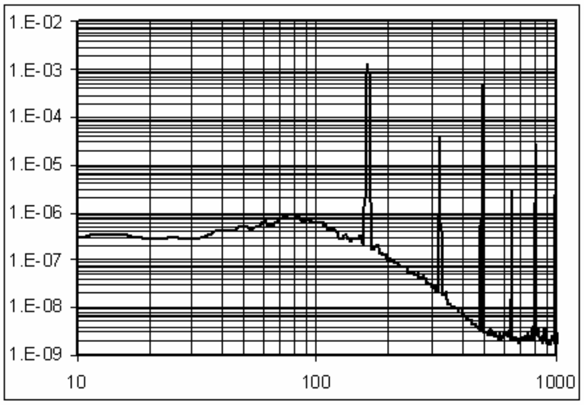

Figure 10. HSS Radial Bearing Position Spectrum
No Moving Notches (10KRPM)

The switch-on frequencies (F_{on}) for the moving notches are just above 10KRPM. Figure 11 (lower) shows the average HSS current spectrum just after the notches have been inserted, at 10.5KRPM. Note that the control currents at the fundamental frequency and its second and third harmonics are no longer present in the command current. This demonstrates that the controller is no longer responding to these rotational noise frequencies. The corresponding bearing current orbit under the same conditions is displayed in Figure 12 (lower). Note that the AC portion of the control current has been decreased dramatically.

In addition to improving controllability and reducing control effort, the moving notches have several additional benefits. First of all, the synchronous notch prevents the controller from responding to true synchronous motion caused by imbalance. If the imbalance force is small enough (that is, the rotor is balanced well enough) that the rotor orbit is reasonable without the synchronous control component, the feed forward control function can be turned off once the synchronous notch is in place. Also, the second and third harmonic notches provide additional protection beyond the fixed notch filters (see next section), against exciting rotor bending modes as these multiples of rotor speed pass through the rotor bending mode frequencies.

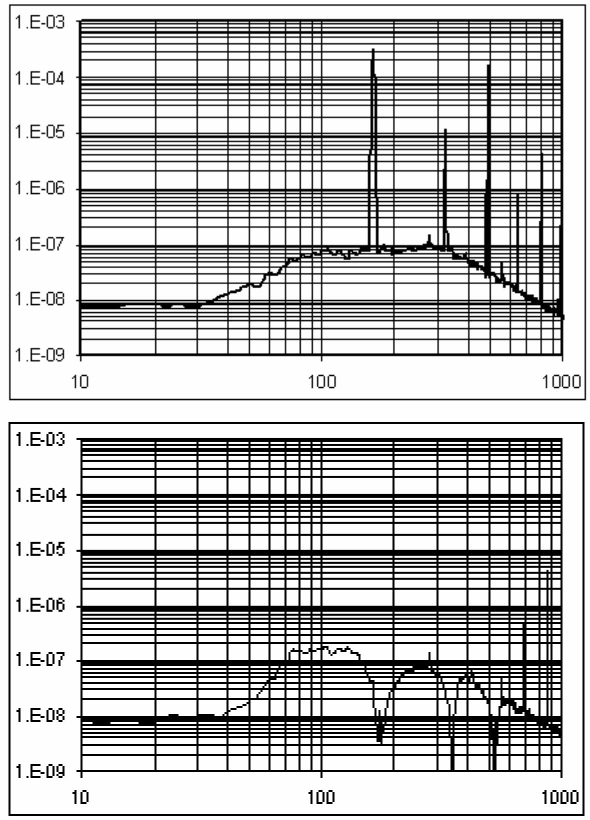

Figure 11. HSS Radial Bearing Current Spectrum
Before and After Moving Notches
(10.0 and 10.5 KRPM)

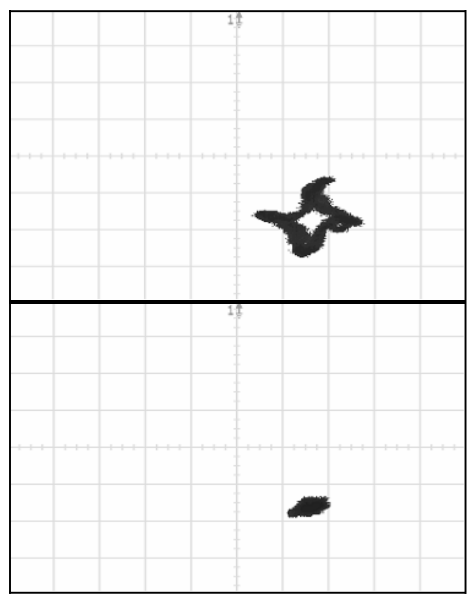
Figure 12. HSS Radial Bearing Current Orbit
Before and After Moving Notches
(10,000 RPM)

Using Moving Notches

The synchronous notch filter cannot be implemented until the rotor frequency is above the rotor forward whirl frequency with sufficient safety margin (forward whirl frequency is determined mainly by the moments of inertia of the rotor, and the controller gain selections; these details are beyond the scope of this paper). In the case of the HSS MB controller, all three moving notches are switched on automatically at 10KRPM. Once the cut-in speed is reached, the fader changes the amount of filter used in the position signal from 0% to 100% over one second. When the rotor slows down and again passes through the switch-on frequency, the filters are gradually cut out using the same approach.

Rotor Bending Modes

The GRC flywheels are designed such that the first bending mode of their rotors must be above the maximum designed rotor speed. Since the maximum design speed is 60000 RPM, the first bending mode in these flywheels must be higher than 1 kHz, to ensure that synchronous rotation does not excite the rotor bending modes. However, even though the rotor synchronous frequency does not pass the rotor bending mode frequencies, harmonics of the synchronous frequency can. In fact, if the controller is set up improperly, the rotor bending modes can be excited with simple levitation at zero speed. When one of the bending modes is excited, the rotor resonates at that bending mode frequency. This should be avoided, as rotor oscillation can cause loss of control and flywheel touchdown to the backup bearings. Even if touchdown is avoided, oscillation of sufficient amplitude or duration can potentially cause rotor cracking.

Any ringing of the bending modes during operation is picked up by the sensors and fed into the controller. Left uncorrected, the controller may try to compensate for these oscillations, and inadvertently increase the oscillation amplitude due to phase lags in the closed loop system. To prevent this, fixed notches are placed on each of the position sensor inputs. These notches keep the controller from attempting to move the rotor at those frequencies, preventing bending mode excitation.

The bending mode oscillations can be seen in the radial position sensor and current sensor spectra. The first two bending modes of the D1 unit are at 1100 Hz and 1500 Hz. To demonstrate the fixed notch operation, the D1 flywheel rotor was allowed to resonate at the first bending mode by levitating at 0 RPM, with controller tuning such that the bending mode was excited. Figure 13 shows the average radial position sensor spectrum (upper) and average bearing current spectrum (lower) for the D1 flywheel under these conditions, with no fixed notching present. Note the oscillation at 1100 Hz in the position sensors; the controller attempts to control this, and drives the rotor into oscillation, as seen by the average bearing current.

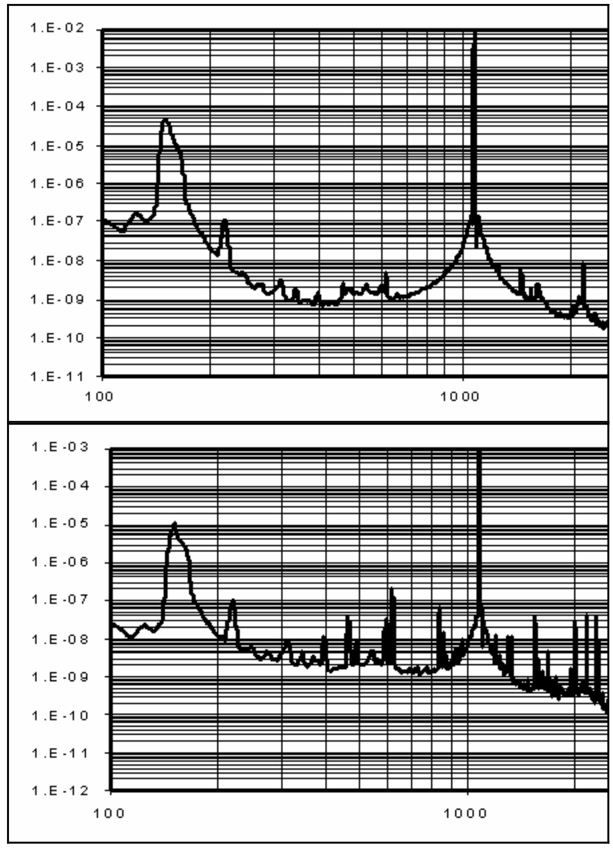

Figure 13. D1 Position and Current Spectrum Levitated, 0 RPM Without Fixed Notching

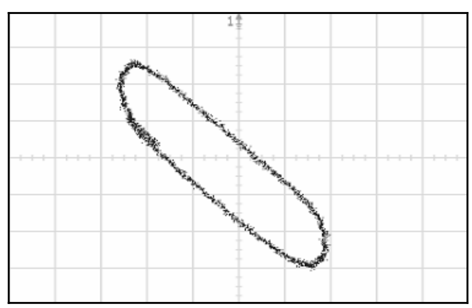

Figure 14. Upper Bearing Radial Current Orbit D1 Levitated at zero RPM, No Fixed Notching

The corresponding current orbit, for the upper radial bearing, is shown in Figure 14; this figure demonstrates the poor quality of the bearing control under these conditions. The bearing currents required to levitate the bearing under these conditions are considerably higher than desired.

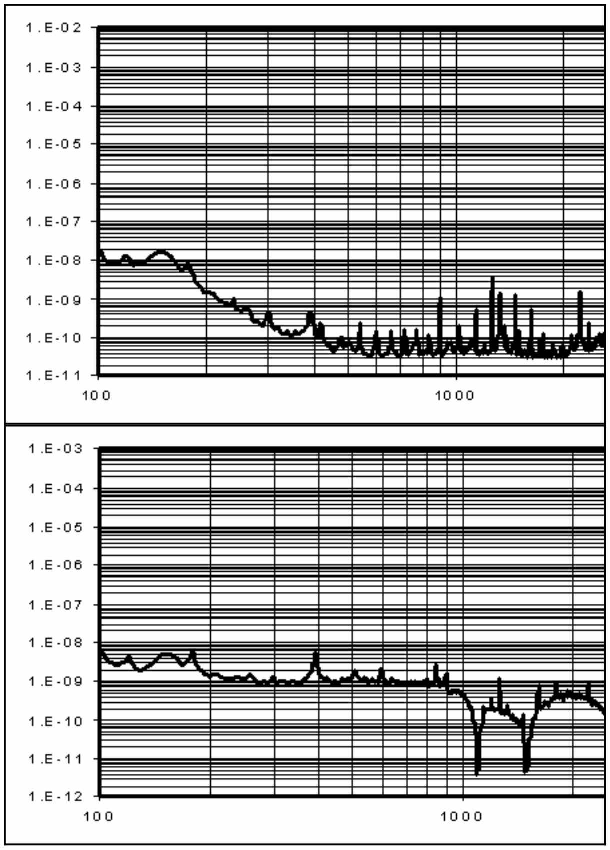

Figure 15. D1 Position and Current Spectrum Levitated, 0 RPM With Fixed Notching

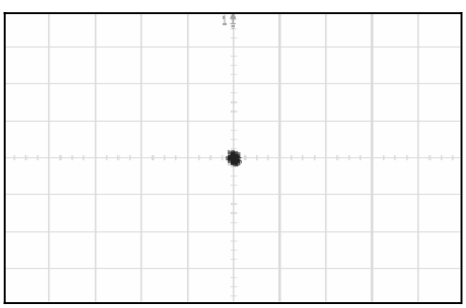

Figure 16. Upper Bearing Radial Current Orbit D1 Levitated at zero RPM With Fixed Notching

Figure 15 shows the flywheel under the same run configuration, with fixed notch filtering in place. Note that the bearing current is notched at the bending frequencies of 1100 and 1500 Hz (Figure 15 lower), and that the corresponding position spectrum shows no ringing at these frequencies (Figure 15, upper). The corresponding current orbit is shown in Figure 16; note that the orbit diameter is significantly decreased by the fixed notches.

Testing and Safety Features

Features which assist with testing of the flywheel system and increase operational safety have been added to the controller system. These best practices have developed gradually over time, and are now a standard part of the GRC MB control systems. This section covers four of these features: safe gain, bearing current zero, bearing hold and excitation inputs.

Safe Gain

The safe gain (SG) feature allows the MB control operator to experiment with MB gain settings during operation without risk of losing control of the rotor. Two sets of gains are used in the SG system: safe gains and test gains. First, a safe set of operating gains for the operating conditions is established; these gains are stored in SG locations. Next, a safe rotor operating range is defined by specifying a circle of allowable travel around the radial set points; this safe operation limit is input to the controller as the SG radius. During flywheel operation, the operator runs the controller on the test gains, and the MB controller continuously checks the rotor position to ensure that it remains within the SG radius. If the rotor moves beyond this circle, the safe gains are automatically switched in in place of the test gains, stabilizing the rotor. A simplified schematic of the SG code is presented in Figure 17.

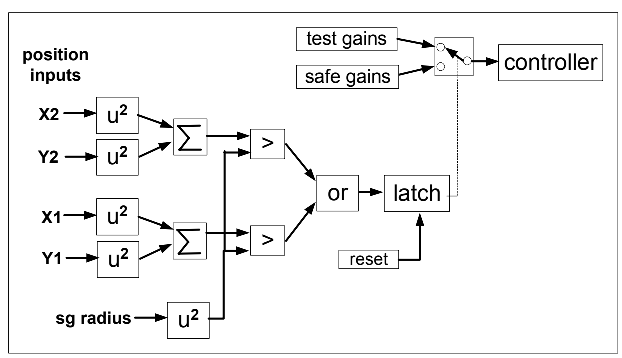

Figure 17. Safe Gain Algorithm

The SG feature is useful for safely determining the stability margins of various MB control gains during operation, and also for making other system measurements (e.g. magnetic bearing negative stiffness) where levitation is intentionally driven to the limit of stability.

Bearing Current Zero

Occasionally, it is helpful to be able to instantly cut off bearing current. One simple method of providing bearing current zeroing is shown in Figure 18. A 9V battery and a pushbutton switch are installed in a small aluminum switch box, which is placed next to the MB control computer and connected to an A/D input on the MB controller. When the controller reads voltage on that input, it switches all five bearing current commands to zero, which immediately drops the rotor onto the backup bearings (see Figure 18).

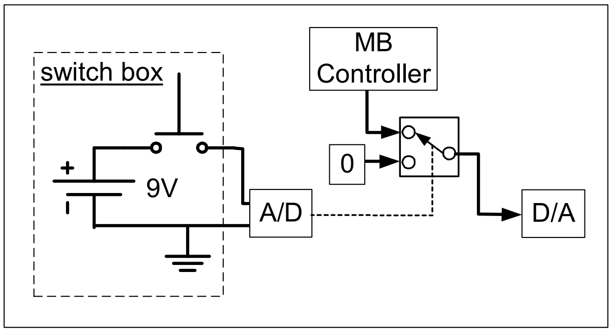

Figure 18. Bearing Current Zeroing Implementation

Bearing current zeroing is particularly helpful when a new MB controller is being tuned for the first time, and instability and crashing are most likely; it allows for a quick, safe way to drop the rotor. It is typically used only at zero RPM or at very low speed; the backup bearings are designed to easily handle a rotor drop under these conditions.

Bearing Hold

The bearing hold feature is similar to the bearing current zero, but is used as a safety shutoff in the event of a high speed crash. When rotor levitation is lost at a high speed, the rotor can bounce around the backup bearings during spin down, or go into a full whirl on the backup bearing such that the entire rotor mass moves with large eccentricity with very large resultant forces, causing considerable damage to the flywheel unit. The bearing hold feature is designed to minimize this damage by pulling the rotor to one side, thus controlling the rotor slowdown.

Hardware for the bearing hold is identical to that of the bearing current zero (Figure 19). However, instead of switching all bearings to zero current, upon sensing voltage, the controller switches all of the radial bearing commands to full current. Thus both radial X and Y are commanded to maximum current, and the rotor is pulled to the wall halfway between +X and +Y (per Figure 1). In the unlikely event of a crash, holding the rotor in one place while it spins down on the backup bearings is more desirable than letting the rotor bounce randomly or go into full whirl.

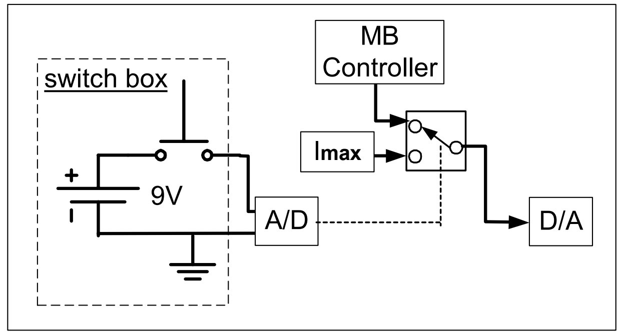

Figure 19. Bearing Hold Implementation

Excitation Input

Excitation inputs allow test signals to be injected into the MB controller. To create an excitation input, a MB controller A/D input is routed in software through five gain blocks, and then summed with either the position inputs at the front of the controller, or the output signals at the back of the controller, depending on the desired effect. Gains available through the HMI allow the operator to select excitation signal size on each bearing axis. A software implementation of an excitation input signal summed with position inputs at the front of the controller is shown in Figure 20.

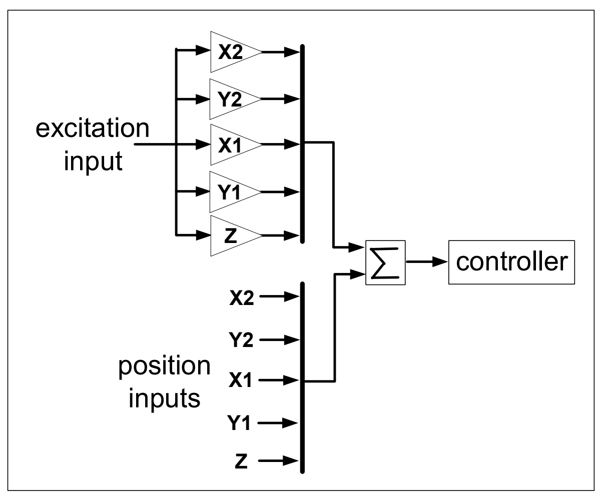

Figure 20. Excitation Input Implementation

Some uses for excitation inputs include testing bearing response to a step input, inserting signals during live controller tuning, and checking controller response to noise.

Conclusions

This paper describes features which improve the performance of magnetic bearing controllers used on high speed flywheel systems. Two general areas are covered: operational improvements, and testing improvements.

The operational improvements described include compensation for rotor imbalance using feed forward correction, compensation for rotational synchronous and harmonic noise using moving notch filtering, and prevention of rotor bending mode excitation using fixed notch filters. Experimental data demonstrating the benefits of each of these features is presented.

The testing improvement features described in the paper are best practices which have been developed over the past few years, and have become standard features in the GRC magnetic bearing controllers. These features include safe gaining, bearing zeroing, bearing hold, and excitation input. Descriptions of each of these features and the benefits they provide, as well as implementation details, are presented.

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Timothy P. Dever, Gerald V. Brown, Ralph H. Jansen, Peter E. Kascak, and Andrew J. Provenza

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National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
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13. ABSTRACT ***(Maximum 200 words)***

A magnetic bearing control system for a high-speed flywheel system is described. The flywheel utilizes a five axis active magnetic bearing system, using eddy current sensors for position feedback to the bearing controller. Magnetic bearing controller features designed to improve flywheel operation and testing are described. Operational improvements include feed forward control to compensate for rotor imbalance, moving notch filtering to compensate for synchronous and harmonic rotational noise, and fixed notching to prevent rotor bending mode excitation. Testing improvements include adding safe gain, bearing current hold, bearing current zero, and excitation input features. Performance and testing improvements provided by these features are measured and discussed.

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